THERMOELECTRIC GENERATOR WITH POLYCRYSTALLINE SILICON MATERIAL

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Abstract. *Compared to bulk technology, the key advantages of integrated micro devices designed with thousands of thermocouples are their ability to handle much higher heat fluxes, their much faster response time as well as the possibility of generating high voltages under small temperature differentials. We develop novel micro devices with a conventional vertically integrated configuration combining high thermal conductivity substrates such as diamond or silicon, integrated circuit technology, and low-pressure chemical vapor deposition (LPCVD) of thick thermoelectric films. A thermoelectric in-plane micro-generator with nanometric films has been fabricated using compatible standard semiconductor technologies (MEMS). The active material is a nanolayer polycrystalline silicon material laid on a dielectric membrane sustained by a silicon frame. Thermal properties of semiconductor nanostructures have recently attracted a lot of attention. This is primarily due to two major factors. The first one is a continuous scaling down of the feature sizes in microelectronic devices and circuits, which leads to an increase in power dissipation per unit area of semiconductor chip. Under such conditions, the influence of size effects on thermal conductivity becomes extremely important for device design and reliability.*

1. Introduction

Technology in the twenty first century requires the miniaturization of devices into nanometer sizes while their ultimate performance is dramatically enhanced. Even after more than 50 years of experience with thermoelectric technology, efficiencies remain relatively low, seldom exceeding 1/8 of the limiting Carnot efficiency. The difficulty is that available materials have limited performance, as characterized by the usual dimensionless figure-of-merit.

The last story was “How thin the thermoelectric module could be?” This time, story goes the other aspect; thinning and miniaturization. You may have thought once at least than what could happen when you make the cross section of the element of the thermoelectric module smaller and smaller, e.g. several tens of microns as illustrated in fig. 1, without changing the heat pumping capacity: I_{max} and number of element couples. What the performance of the miniaturized module could be?

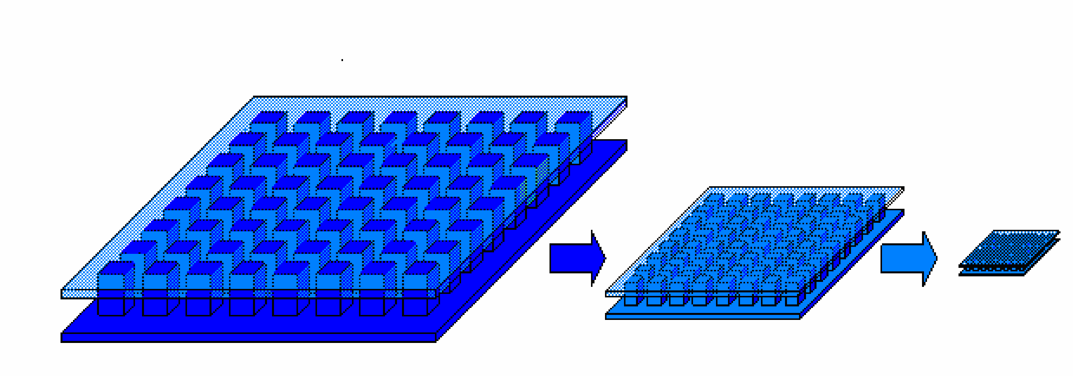


Fig. 1 Shrinking a TEC without changing element I_{max} and number of couples

As we keep the Imax and element couples unchanged, miniaturization naturally suggests a detrimental effect on maximum temperature difference, ΔT_{max} , from increasing electrical resistance of cooper electrode.

Thermo-electrical materials and structure that have characteristics length scales that are comparable to such quantities as mean free paths, domain sites in ferromagnets and ferroelectrics, coherence lengths of phonons, and correlation lengths of collective ground states like superconductivity. The main point is that nanotechnologies are not just the next step in miniaturization beyond micro-scale technologies such as micro-electro-mechanical systems. Nanotechnologies instead represent a qualitatively new scale of materials where quantum mechanics phenomena manifest themselves in significantly new behaviors. These new nanotechnology materials have exciting new properties and characteristics that hold the promise to impact all the applications and technologies discussed and create exciting new technologies and advancements. These materials also hold many new and exciting challenges however, as we have remarkably little experience or intuition for what phenomena and behaviors to expect in these new materials.

A thermoelectric generator convert’s heat (Q) into electrical power (P) with efficiency η.

$$P = \eta Q \qquad (1)$$

The amount of heat, Q, that can be directed though the thermoelectric materials frequently depends on the size of the heat exchangers used to harvest the heat on the hot side and reject it on the cold side. As the heat exchangers are typically much larger than the thermoelectric generators themselves, when size is a constraint (or high P/V is desired) the design for maximum power may take precedence over maximum efficiency.

It is customary to express the usefulness of a thermoelectric material for use in refrigeration or power generation applications in terms of the dimensionless quantity ZT where T is the temperature (in degrees Kelvin) and Z is the thermoelectric figure of merit:

$$Z = \frac{\alpha^2 \sigma}{K} \qquad (2)$$

Here S is the thermoelectric power or Seebeck coefficient, σ is the electrical conductivity and k is the thermal conductivity. Large values of ZT require high S, high σ, and low k. Since an increase in S normally implies a decrease in σ because of carrier density considerations, and since an increase in σ implies an increase in the electronic contribution to k as given by the Wiedemann–Franz law, it is very difficult to increase Z in typical thermoelectric materials.

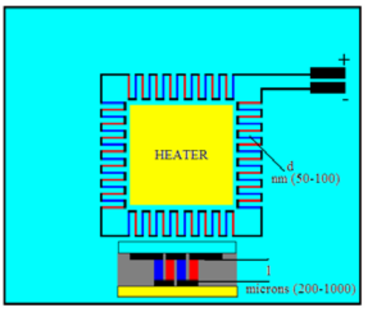
Reduced dimensionality offers one strategy for increasing ZT relative to bulk values. The use of low-dimensional systems for thermoelectric applications is of interest because low dimensionality provides: (1) a method for enhancing the density of states near EF, leading to an enhancement of the Seebeck coefficient, (2) opportunities to take advantage of the anisotropic Fermi surfaces in multi-valley cubic semiconductors, (3) opportunities to increase the boundary scattering of phonons at the barrier-well interfaces, without as large an increase in electron scattering at the interface, (4) opportunities for increased carrier mobilities at a given carrier concentration when quantum confinement conditions are satisfied, so that modulation doping and δ-doping can be utilized.

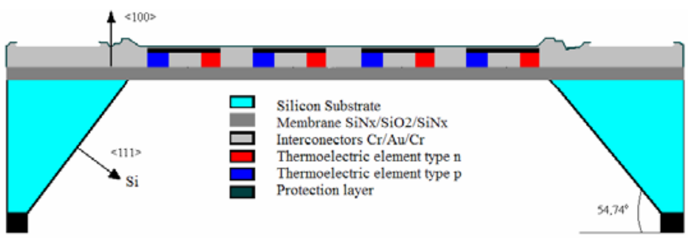
A good thermoelectric material has a Seebeck coefficient between 100 μV/K and 300 μV/K; thus, in order to achieve a few volts at the load, many thermoelectric couples need to be connected in series to make the thermoelectric device.

For large electrical power generation applications traditional dynamic thermal to electric generators have several times the efficiency of a thermoelectric system. However, such dynamic systems are expensive and do not scale easily for small applications. When high quality combustible fuel is available, internal combustion engines are cost effective and reasonably efficient in the 100 W to 100 kW range but tend to be noisy. For applications requiring less than 100W, the scalability of thermoelectrics gives them a clear advantage.

2. Experimental techniques and sample preparation

A thermoelectric in-plane micro-generator has been fabricated using compatible standard semiconductor technologies. The active material is a fine-grained polycrystalline silicon material laid on a dielectric membrane sustained by a silicon frame. A simplified analytical one-dimensional model of the micro-generator has been made to find the optimum thermoelectric film thickness and thermoelectric leg length. The optimal geometry of the micro-generator depends on the thermal properties and emissivity of the materials as well as on its working environment i.e. air or vacuum and on its operational mode. These investigations have been extended to a more realistic geometry of micro-generators and to more efficient thermoelectric materials, using a numerical model. The performance of such micro-generators is predicted for various materials and geometry combinations. There is a growing demand in consumer electronic for small, cheap and environmental-friendly power sources. This demand is driven by progresses made in electronic components miniaturization and smart power management. Thermoelectric technology can readily be miniaturized using micro technology because no moving part is required, which makes it a good candidate to power wearable consumer electronics or very small spacecrafts.





Two modes of working are anticipated for the in-plane thermoelectric micro-generator. The first mode of working (i.e. mRTG) is when the heat source is on the membrane (Fig. 2a). The silicon frame that sustains the membrane is the cold side. A large temperature difference along the thermoelectric legs should be created with small heat sources because the thickness of the area covered by the thermoelectric leg is thin (1250 nm) and its thermal conductivity is low (3.9 $W.m^{-1}.K^{-1}$). This large temperature difference is interesting to get high efficiency.

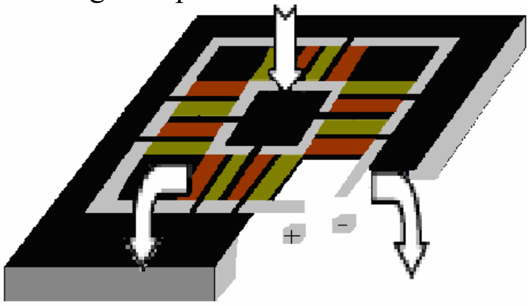


Fig. 2a`

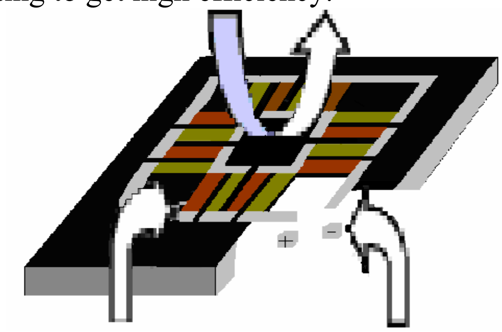


Fig. 2b

The second mode of working (i.e. BHPW) takes advantage of the large surface-to-volume ratio of the membrane to use it as a radiator, the hot side being the silicon frame (Fig. 2b). The heat source may be the heat generated by a living creature while the coolant could be simply air.

3. Results and discussions

Tabel 1. Physics properties of used materials

	Electric Conductivity [$\Omega^{-1}m^{-1}$]	Thermoelectric Power [µV/K]	Thermic Conductivity [$Wm^{-1}K^{-1}$]	Figure of merit ZT 300K
Polisillicium	50000	165	14,5	0,028
SiGe	102850	114	4,7	0,085
Bi_2Te_3	100000	195	1,9	0,60

Tabel 2. a) Thermoelectri Microgenerator in function mode, mRTG, diaphragm size is 1,6 x 1,6 mm, microgenerator contains 50 thermoelectric pairs, heat power on diaphgram is of: 1 mW. ΔV and W are outgoing tension tensiunand useful electric power.

	ε	lT [µm]	dT [nm]	ZTm	ΔT [K]	ΔV [V]	W [µW]
Polisillicium	0	180	150	0,014	8,0	0,13	0,090
	1	150	190	0,016	5,1	0,084	0,058
SiGe	0	180	460	0,043	7,9	0,091	0,27
	1	150	570	0,048	5,0	0,057	0,16
Bi_2Te_3	0	180	900	0,27	8,1	0,16	1,5
	1	150	1150	0,30	5,0	0,098	0,94

An average of electric conductivity and thermoelectric power is obtained counting on materials ability of both n and p type because the ZT values calculated starting from this mediumm values, are equal with the ZT values of the n-p couple.

Tabel 2. b): Results obtained on thermoelectric microgenerators in function mode mRTG, diaphgram size is of 1,6 x 16 mm, microgenerator contains 1000 thermoelements, heat power on diaphgram is of 5 mW.

	ε	lT [μm]	dT [nm]	ZTm	ΔT [K]	ΔV [V]	W [μW]
Polisillicium	0	270	140	0,014	9,9	1,6	0,58
	1	200	240	0,018	4,2	0,70	0,24
SiGe	0	270	410	0,041	9,9	1,1	1,7
	1	200	750	0,053	4,1	0,47	0,7
Bi_2Te_3	0	270	840	0,26	9,8	1,9	9,4
	1	200	1450	0,34	4,2	0,83	4,0

Tabel 2 c): Results obtained on thermoelectric microgenerators in function mode mRTG, diaphgram size is of 1,6 x 16 mm, microgenerator contains 1000 thermoelements, heat power on diaphgram is of 10 mW.

	ε	lT [μm]	dT [nm]	ZTm	ΔT [K]	ΔV [V]	W [μW]
Polisillicium	0	270	140	0,014	20	3,3	2,3
	1	200	240	0,018	8,4	1,4	0,98
SiGe	0	270	410	0,042	9,9	2,3	6,7
	1	200	750	0,053	19,9	0,93	2,8
Bi_2Te_3	0	270	840	0,26	19,6	3,8	37
	1	200	1450	0,34	9,4	1,6	16

Tabel 3. a): Results obtained on thermoelectric microgenerators in function mode of thermoelectric sample (BHPW), diaphgram size is 1,6 x 1,6 mm, microgenerator contains 100 thermoelements, transfer coefficient h is equal with 52,6 W m^{-2} K^{-1}.

	lT [μm]	dT [nm]	ZTm	ΔT [K]	ΔV [V]	W [μW]
Polisillicium	220	750	0,024	-7,4	0,12	0,29
SiGe	230	2300	0,073	-7,5	0,086	0,86
Bi_2Te_3	220	4400	0,49	-7,4	0,14	4,87

Tabelul 3. b): Results obtained on thermoelectric microgenerators in function mode of thermoelectric sample (BHPW), diaphgram size is 1,6 x 1,6 mm, microgenerator contains 1000 thermoelements, transfer coefficient h is equal with 52,6 W m^{-2} K^{-1}.

	lT [μm]	dT [nm]	ZTm	ΔT [K]	ΔV [V]	W [μW]
Polisillicium	290	1300	0,026	-8,3	1,37	3,5
SiGe	300	4000	0,078	-8,3	0,95	10
Bi_2Te_3	290	7800	0,54	-8,2	1,6	57

Tabel 3. c): Results obtained on thermoelectric microgenerators in function mode of thermoelectric sample (BHPW), diaphgram size is 1,6 x 1,6 mm, microgenerator contains 100 thermoelements, transfer coefficient h is equal with 26,3 $Wm^{-2}K^{-1}$.

	lT [μm]	dT [nm]	ZTm	ΔT [K]	ΔV [V]	W [μW]
Polisillicium	330	800	0,025	-7,9	1,30	1,7
SiGe	340	2500	0,074	-7,8	0,89	4,9
Bi_2Te_3	330	4900	0,50	-7,7	1,5	27

4. Conclusion

Compared to large, traditional heat engines, thermoelectric generators have lower efficiency. But for small applications, thermoelectrics can become competitive because they are compact, simple (inexpensive) and scaleable. Thermoelectric systems can be easily designed to operate with small heat sources and small temperature differences. Such small generators could be mass produced for use in automotive waste heat recovery or home co-generation of heat and electricity. Thermoelectrics have even been miniaturized to harvest body heat for powering a wristwatch.

In-plane thermoelectric micro-generators are very promising for powering micro-systems. A heating power of about 100 mW may be enough to produce 1 mW of useful electrical power in vacuum, using thin film technology.

Thermoelectric micro-generators based on thick-film technology will be able to work in air. They will take advantage of their large surface-to-volume ratios to improve the coupling between the heat reservoirs and the thermo elements. This makes it a very promising device to efficiently convert heat wasted by our body to electrical power. A compact thermoelectric device may be able to produce as much as 60 mW with an output voltage of about 1.5 Volt. Nevertheless, the electrical contact resistances have to be lowered to a satisfactory level, good thermoelectric materials have to be used and thermoelectric thick-film technology needs to be improved or developed to get films with good thermoelectric properties at an acceptable economical cost.

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